PERSPECTIVE

It's Time to Reinvent the Transistor!

Thomas N. Theis* and Paul M. Solomon

A breakthrough in materials could refresh and sustain the information technology revolution.

Have you noticed that computers have stopped getting faster? Microprocessor clock frequencies plateaued around 2005, a stunning break after a decades-long run of ever-compounding improvements in computing speed. The cause is a breakdown of the simple constant-electric-field scaling rules that had guided the shrinking of field-effect transistors (FETs) for decades (*1*). As transistors shrank, they switched faster and used less power to switch. But constant-field scaling requires that operating voltages decrease in tandem with transistor dimensions. In recent years, this has become increasingly difficult to follow because a minimum gate voltage swing is necessary to switch the device from an "off" (low-current) state to an "on" (high-current) state. If that swing is too small, the device designer is faced with two bad choices: excessive leakage current in the nominally "off" state or low current (slow circuits) in the nominally "on" state. In other words, the choice is between computers that run hot while doing nothing or computers that run slower than previous models! Thus, over the past 10 years, the industry gradually moved from constant-field scaling toward constant-voltage scaling (*2*). Companies continue to shrink the transistor, emphasizing the increasing number of parallel processors (cores) they can place on a single silicon chip. But with power supply voltages stuck at about 1 V, increasing clock frequencies as in the past would result in unsupportable increases in power dissipation and heat generation. The transistor is rapidly approaching its ultimate physical limits.

The only way to decisively break the power dissipation bottleneck is to change the physics of transistor operation in ways that facilitate further reduction of operating voltage. That means increasing the nonlinearity of the switching behavior so that a much smaller swing in gate voltage is needed to switch the device from off to on. In a conventional FET, the sharpness of this turn-on is limited by the leakage current in the off state. This current arises from charge carriers in the source electrode that are thermally excited over an energy barrier controlled by the voltage on the gate electrode and thus enter the conducting channel of the device (Fig. 1). However, there are other ways to gate the flow of carriers through the channel.

The interband tunnel FET (*3*) uses band-to-band tunneling to filter the energy distribution of charge carriers in the source. If electrons are the charge carriers, the injected electrons are limited in energy from below by the conduction band in the channel and from above by the valence band in the source (Fig. 2). This cuts off the hot Boltzmann tail of carriers in the source and should produce a much sharper turn-on. Promising behavior was observed in a carbon nanotube device (*4*). Only limited success has been obtained so far with silicon-channel devices (*5*). Presumably this is because band-to-band tunneling transitions in this indirect band-gap material are not allowed by momentum conservation unless a phonon is involved. Interest may therefore be shifting to direct-gap semiconductors in which it should be possible to engineer larger on-state tunneling currents (*6*). The best approach may be to incorporate a direct-gap material (such as a III-V compound semiconductor nanowire or a carbon nanotube) in a wirelike device geometry, which, compared with a conventional planar device structure, will allow more abrupt modulation of energy bands for increased band-to-band tunneling and thus increased current in the on state.

Another way to increase the sharpness of the FET turn-on is to incorporate an internal gain mechanism so that a small voltage swing on the gate electrode causes a larger swing of the internal potential that gates the flow of current. Salahuddin and Datta (*7*) proposed a device with a gate insulator stack consisting of a layer of ferroelectric material sandwiched between conventional dielectric layers. The energy barrier presented by this gate structure to charge injection depends on the polarization of the ferroelectric layer, which, because it arises from a collective effect, switches abruptly between two polarization states. A key insight was the recognition that layer thicknesses and material properties could be engineered so as to greatly suppress the undesirable hysteretic behavior that would normally be expected from such a gate structure while still amplifying the effect of the gate potential on the channel potential. One potential drawback is that the shortest reported ferroelectric switching times, 70 to 90 ps (*8*), are too long to be of interest for fast FET logic, where switching can occur in 1 ps or less. But Kopp and Mannhart (*9*) have predicted similar effects in electronic systems exhibiting strong electron exchange and correlation effects. [See also the Review by Mannhart (*10*).] Regardless, Salahuddin

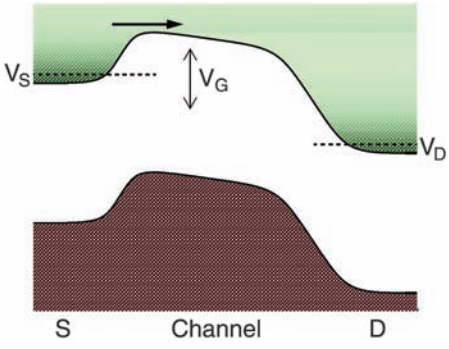

Fig. 1. The voltage V_G applied to the gate contact of a FET determines the energy barrier for injection of charge carriers from the source contact (S) into the channel. Leakage current in the off state (shown) is due to carriers in the hot tail of the equilibrium energy distribution of carriers in the source. Shade of gray indicates charge carrier concentration. D indicates the drain contact.

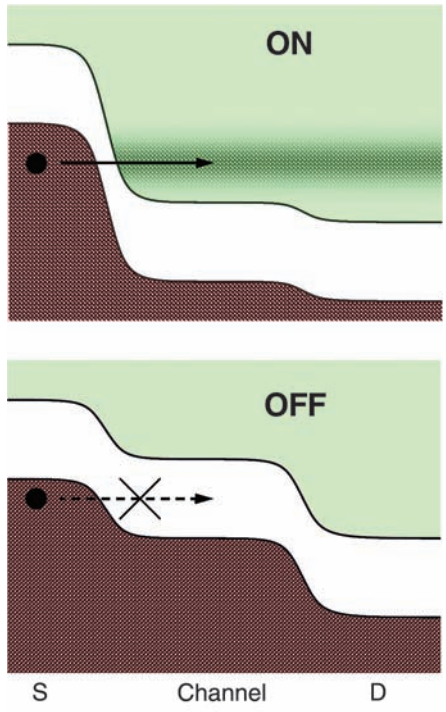

Fig. 2. Operating principle of a tunnel FET, after Appenzeller *et al.* (*4*). The upper (conduction) and lower (valence) energy bands are (**top**) crossed in the on state and (**bottom**) uncrossed by the gate voltage in the off state.

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and Datta have made a conceptual breakthrough by showing how a collective switching effect can be exploited to improve the nonlinearity of an FET. Further invention appears likely.

Both the tunnel-FET and the ferroelectric-gate FET promise low voltage and thus ultra-low-power switching, but as presently conceived these devices may not be fast. Can new direct-gap materials and novel device structures reduce the internal device resistance presented by the band-to-band tunneling barrier? Can the switching speed of ferroelectric materials be markedly increased? Can the highly correlated electronic systems flagged by Kopp and Mannhart be incorporated into practical channel and gate electrode structures to produce similar but faster switching? These are great challenges for materials scientists. A breakthrough could refresh and sustain the information technology revolution for decades to come.

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PERSPECTIVE

An Emergent Change of Phase for Electronics

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Correlated electrons in transition metal oxides can form a variety of electronic phases. The phase change between these various states gives rise to novel device functions, including sensing, signal conversion, and nonvolatile memory, and is now at the frontier of research on "emergent research device materials." Those oxide devices may have an advantage over conventional semiconductor devices for added functionality and future downsizing to the nanoscale. The elucidation of the microscopic physics behind their operation is a key step for further development.

In the 2007 edition of the *International Technology Roadmap for Semiconductor Devices*, a new chapter was created—"Emergent Research Device Materials"—in which the needs for a new generation of devices based on novel mechanisms were emphasized (*1*, *2*). Strongly correlated electron devices using complex oxides occupy an important position along this direction. Compared with conventional semiconductors, the quality of oxide materials for devices was believed to be substantially inferior partly because of their chemical complexity. Recent progress in oxide fabrication technology, however, is altering this conventional belief. For example, high-mobility two-dimensional (2D) electron gases were successfully formed in oxides, including (Mg,Zn)O/ZnO heterointerfaces exhibiting the quantum Hall effect (*3*) and delta-doped $SrTiO_3$ heterostructures exhibiting 2D superconductivity (*4*).

The electric and magnetic properties of transition-metal oxides are often dominated by electrons in *d*-orbitals. The large Coulomb repulsion between electrons accommodated in the spatially constrained *d*-orbitals tends to block the motion of electrons from one atom to another, and the electrons are highly interacting. Just like interacting atoms and molecules, the correlated electrons can form solid (insulator), liquid (metal), and superfluid (superconductor) states inside the solid. The presence of the electron's three degrees of freedom—charge, spin, and orbital—enrich these electronic phases further (Fig. 1A). Complex combinations of charge-, spin-, and orbital-ordered states indeed appear in the phase diagrams of transition metal oxides.

These rich electronic phases compete with each other in a delicate balance. Even a minute external perturbation by an applied electric or magnetic field or pressure can induce a phase change (*5*), giving rise to a dramatic response to external stimuli. The coexistence of charge and spin degrees of freedom can bring about cross-couplings between the electric and magnetic response. This coupling is the hallmark of phase-change functions in transition metal oxides, rendering them useful as sensors and memories and for signal conversion. Well-known examples of this approach are so-called "colossal magnetoresistance" (CMR) devices that use complex Mn oxides for magnetic field sensors (*6*). Large regions of their phase diagrams show a critical competition between a ferromagnetic metal (liquid) and a charge-ordered insulator (solid). In such a situation, the electron solid is melted easily by the application of magnetic fields, and the ferromagnetic metal state is stabilized, which manifests itself as an orders-of-magnitude change in resistivity. Melting of the electron solid also occurs by the irradiation of pulsed photons (*7*), which can form the basis of an optical switch. Multiferroics, in which ferromagnetism (or antiferromagnetism) coexists with ferroelectricity, falls into the same category of phase-change function (*8*). The critical control of the spin state via magnetic field allows the control of electric polarization, including its orientation.

Control of magnetization via electric field is now envisaged (*9*), which should affect applications in spintronics, in which the spin of the electron in addition to its charge is used to convey information. A critical electronic phase change, if coupled with a chemical phase change, produces a nonvolatile memory effect. With demand for increased storage capacity, modern nonvolatile memory based on semiconductors, such as flash memory, has been downscaled successfully but is expected to soon reach fundamental physical limits. To achieve further storage density, a number of novel random access memories (RAMs) have been studied, including FeRAM (ferroelectric), MRAM (magnetic), and PRAM (phase change). ReRAM (resistance), which is based on transition metal oxides, recently emerged as a new memory candidate (*10*). The device has a capacitor-like structure with a metal/oxide insulator/metal (MIM) stack and, after the first electric field stress (the forming process), switches between high- and low-resistance states with the application of short voltage pulses.

Such resistance-switching phenomena had been observed in MIM structures many decades ago (*11*). This gained renewed interest because of the demonstration of a MIM RAM device that uses charge-ordered $(Pr,Ca)MnO_3$ (*12*) and Mott insulating NiO (*13*). In several cases, the

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